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A Receiver-based Routing Protocol for Cognitive Radio Enabled AMI Networks

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***Abstract*—It is expected that the use of cognitive radio for smart grid communication will be indispensable in near future. Recently, RPL for cognitive radio enabled Advanced Metering Infrastructure (AMI) networks is attractive. Our objective in this paper is to propose an enhance RPL to improve efficiency and reliability of cognitive radio enabled AMI networks. Our protocol is receiver-based in nature, which can achieve better reliability of the network along with protecting the primary users as well as meeting the utility requirements of secondary network. System level performance evaluation shows the effectiveness of proposed protocol as a viable solution for practical cognitive AMI networks.**

***Index Terms*—Smart grid, Cognitive radio networks, AMI, Routing, Directional mutation ant colony optimization.**

I. Introduction

THE legacy electric power grid, which has been used for many years, meets some problems such as insecure, energy inefficient and frequent transmission congestion and even failure [1], [2]. The next generation of electric grid, namely, *smart grid*, is expected to supply improved serve with more reliability, efficiency, agility and security [3]. It will upgrade power distribution and management by incorporating advanced bi-directional communications, automated control and distributed computing capabilities. It makes providers distributors, and consumers of electricity can have a real time awareness of operating requirements and capabilities. The capacity gathers remote and timely information from grid equipment in different areas and make the use of energy more efficiency [4]–[7].

One key element of information gathering in smart grid is the *Advanced Metering Infrastructure* (AMI), which acts as a control center for storage, processing and management of meter data in order to be used by different applications [4]. The AMI networks can contribute for smart grid in several ways. It provides two-way communications through which utilities can keep track of consumers? electricity usage, monitor power quality, inform consumers the latest electricity prices, all on a real-time basis. Several communication technologies are currently under consideration for AMI networks, such as cellular [8], WiMAX [9], Power Line Communications (PLC) [10], wireless sensor networks (WSNs) [11], Multi-hop wireless mesh network [12], etc. Each of these technologies has its own pros [13]. However, no literature studies the energy efficiency of AMI network, which will be a practical issue, when smart grid and AMI are popularized in our daily life. For energy-efficient communications, both transmit power and other parts of energy consumption need to be taken into consideration [6], although, this additional energy consumption may change the fundamental tradeoff between energy efficiency and data rate [14].

On the other hand, *cognitive radio* (CR) [15] is viewed as an effective approach to address the spectrum scarcity and spectrum inefficiency issue in wireless networks, which also can play an important role in mitigating interference and improving energy efficiency for future mobile cellular networks [16]. In CR networks, unlicensed users (secondary users) dynamically access the frequency band/channel whenever the licensed user (primary user) is absent and need to vacate the band/channel whenever the latter is detected. Therefore, several motivations for using cognitive radio (CR) technology for smart grid communications are proposed [17]. Recently, a number of studies (e.g., see [12], [15]) have been presented on different smart grid related platforms regarding the application of CR for smart grid communication.

Against this background, our objective in this paper is to enhance the routing protocol for Cognitive AMI networks. In this regard, we propose CRB-RPL which is a receiver-based routing protocol. CRB-RPL is designed with special emphasis on efficiency and reliability requirements of AMI in smart grid environments. CRB-RPL exploits the broadcast nature of wireless medium and multiple receivers competition approach to improve the reliability of the network along with reducing the number of retransmissions. The rest of the paper is organized as follows. Section II presents the CRB-RPL framework followed by the performance evaluation in Section III. Finally the paper is concluded in Section IV.

II. CRB-RPL Framework

A. Overview of CRB-RPL

A key aspect of Cognitive AMI network is cognitive enabled through spectrum sensing [18], [18], [19]. Therefore, in CRB-RPL, nodes monitor the current channel periodically to check PU activity before occupying it for transmission. It must ensure protection for both PU transmitters and PU receivers [20]–[22]. Especially, the latter is particularly important for those PU applications with where unidirectional transmission, such as, TV broadcast.

A key aspect of CRB-RPL is *preamble sampling* for achieving high energy efficiency. In preamble sampling approach (also known as asynchronous low power listening), each node selects its sleep/wakeup schedules independently of other nodes. In most time, nodes are in sleep mode, but wake up for a short duration called *clear channel assessment* (CCA) in *checking interval* (CI) to check whether there is an ongoing transmission on the channel. To avoid deafness, the sender node transmits a long preamble with the same length as CI, followed by the data packet, to ensure that all receivers detect the preamble and obtain the data frame.

CRB-RPL is inherently *receiver-based* in nature. In *sender-based* protocol (such as CORPL [13]), the sender selects a receiver node from its neighbor table and includes the receiver's address in the packet header. Unlike sender-based protocol, in the receiver-based, a sender node transmits its data without defining a particular node as a receiver. All the neighboring nodes within communication range of the sender node receive the data packet. Based on the information received from the preamble, each individual node decides if it is eligible to participate in forwarding the data. Receivers compete in an *elective* process and the winner forwards the data towards gateway.

B. System model

The static multi-hop wireless AMI network is considered here, which consists of different smart meters (nodes) and a meter concentrator (gateway node). It is assumed that the smart meters are CR enabled. A single radio transceiver is equipped in each smart meter which can be tuned to any channel in the licensed spectrum. It is assumed that N stationary PU transmitters with known locations and maximum coverage ranges are in this research.

We consider J stationary PU transmitters (and hence J available channels) with known locations and maximum coverage ranges. The PU (transmitter) activity model for the j^{th} channel is given by a two state independent and identically distributed random process, namely, $busy$ and $idle$. Let S_b^j denote the state that the j^{th} channel is busy (PU is active) and S_i^j the state that the j^{th} channel is idle with probability. We assume that a node employs energy detection technique [18] for primary signal detection wherein it compares the received energy (E) with a predefined threshold (σ) to decide whether the j^{th} channel is occupied or not i.e.,

$$Sensing\ Decision = \begin{cases} S_b^j & \text{if} \quad E \geq \sigma \\ S_i^j & \text{if} \quad E < \sigma \end{cases} \tag{1}$$

The two principle metrics in spectrum sensing are the detection probability (P_d), and the false alarm probability (P_f). A higher detection probability ensures better protection to incumbents, whereas a lower false alarm probability ensures efficient utilization of the channel. False alarm and detection probabilities for the j^{th} channel can be expressed as follows.

$$P_f^j = Pr\{E \geq \sigma | S_i^j\} = Q\left(\frac{\sigma - 2n_j}{\sqrt{4n_j}}\right), \tag{2}$$

$$P_d^j = Pr\{E \geq \sigma | S_i^j\} = Q\left(\frac{\sigma - 2n_j\left(\gamma_j + 1\right)}{\sqrt{4n_j\left(2\gamma_j + 1\right)}}\right), \tag{3}$$

where $Q(\cdot)$ denotes Q function, which is the complementary error function, and γ_j and n_j denote the signal-to-noise ratio (SNR) of the primary signal and the bandwidth-time product for the j^{th} channel respectively.

C. Protocol Description

In Cognitive AMI, it needs to maintain network state information by using Directed Acyclic Graphs (DAGs), which are directed graphs wherein all edges are oriented without no cycles exist. Each DAG created has a root node which acts as a gateway. Each client node (node for short) in the DAG is assigned a rank to show its virtual position in the network. The root node has the lowest rank and the rank monotonically increases in the downward direction. In order to construct a DAG, the gateway broadcasts a control message called DAG Information Object (DIO) containing relevant network information including the DAGID to identify the DAG and the rank information along with the objective function for rank computation. Any node that receives the DIO message and compute its rank based on the parent nodes' ranks.

As we want to retain the DAG structure, therefore, in CRB-RPL the construction process follows a similar procedure as RPL (more details of Cognitive AMI and RPL can be found in literature [13]). After detecting a vacant channel, the gateway node transmits DIO messages periodically to identify client nodes and update node ranks. According to the CR environment, we utilize the $Cognitive\ Radio\ Transmission\ Factor$ (CRTF) as the default metric for rank computation, which considers about not only QoS of link but also protection of PU receivers, which is given by

$$C_a = \frac{1}{\rho_{ab} \cdot (1 - \varepsilon_a)} \tag{4}$$

where ρ_{ab} is the probability of b receiving a transmission from node a, and $\varepsilon_a = \sum_{j=1}^{N} c_{aj}$ denotes the net overlapping area of node a with all PU transmitters.

ρ_{ab} accounts for the link quality. It has been shown that the cooperative gain becomes less significant when the inter-forwarder link success probabilities are low [23]. ε_a is another key factor, which represents the fractional area between client nodes and PU transmitters. In order to reduce interference to PU receivers, the routes for the secondary network should be selected such that they pass through regions of minimum coverage overlap with the PU transmission coverage. The fractional area of node a transmission coverage under the coverage of j^{th} PU transmitter is given by (5), where R_j and r_a denote the coverage radii of the j^{th} PU transmitter and the node a respectively, and d_{aj} is the distance between the two.

The CRTF of a node will be measured and updated at the beginning of a DIO period. The rank of node a can be given by

$$Rank_a = \min\{Rank_p + k \cdot C_a\} \tag{6}$$

$$c_{aj} = \frac{1}{\pi}\cos^{-1}\left(\frac{1}{2d_{aj}r_a}\right) + \frac{R_j^2}{\pi r_a^2}\cdot\cos^{-1}\left(\frac{d_{aj}^2 + R_j^2 - r_a^2}{2d_{aj}R_j}\right) - \frac{1}{2\pi r_a^2}\sqrt{\left\{(R_j + r_a)^2 - d_{aj}^2\right\}(d_{aj} + r_a - R_j)(d_{aj} - r_k + R_j)} \tag{5}$$

where k is a constant; $p \in \mathbf{P}$, $\mathbf{P}$ denotes the parent node set of node a and ρ_{ag} denotes the probability of node p receiving a transmission from node a.

In CRB-RPL, nodes need not have a has a forwarder set. The sender broadcast the signal of the packet. It is the receiving nodes that decide the next hop. When a node S wants to send data to the gateway node, it broadcasts the packet towards all its hop neighbors (within the transmission range). Firstly, it performs spectrum sensing (with duration given by T_s) to detect any PU activity. If the channel is detected as busy with PU transmission, namely, S_b^j, the sender node goes to sleep mode and waits for the available channel. The spectrum sensing operation is repeated after a duration of checking interval (T_C). If the PU is detected to be absent, namely, S_i^j, S starts transmitting the preamble followed by the data. The preamble, which last for T_{pr}, consists of multiple micro-frames and each of duration T_m. The micro-frames contain identification information for neighboring nodes to distinguish between PU transmission or sensor node transmission. All the nodes within the transmission range of S will detect a few micro-frames of the preamble and extract necessary information (e.g., sequence number of the data).

For example, three neighboring nodes of S (i.e., nodes A, B, and C) are eligible to forward the data towards the gateway node. They wake up and receive the data transmitted from S. If the received data packet is detected to be erroneous, it will be simply discarded. The nodes, which received the data packet, do not send any Acknowledgement (ACK) message. It is noted that nodes can only receive the packets from higher-ranked nodes. If the sender has a lower rank, the receiver will discard the data receiving. Each node sets a timer Δt before broadcasting the packet, which is relative to the node' rank. The node with lower rank sets a shorter timer and is more likely to forward the packet. The timer is given by

$$\Delta t = \omega_1 \cdot Rank + \omega_0 \tag{7}$$

where ω_1 and ω_0 are constants.

If no channel is available, the node goes back to sleep mode for a duration T_C. Moreover, when a node's transmission is found, each node should check the sequence number. If the sequence number matches with its own, which means that the same packet has been transmitted by another node. Hence, it will discard the packet. Otherwise, the node gets a free channel and transmits the packet. If no neighbor nodes forward the packet in a contention window (T_{CW}), the sender (S) will retransmit the packet. T_{CW} is set according to the transmission radius of sender nodes. In case of multiple hops, the same operation continues until the data is received by the gateway.

The algorithm of receiver-based transmission is shown in Algorithm 1.

Algorithm 1: RECEIVER-BASED NEXT-HOP COMPETITION MECHANISM

```
i → node i
i receives the preamble and extracts information
if the sender has a higher rank than i then
    i receive the data
    waiting for Δt_i
    i starts spectrum sensing
    if another node broadcasts the preamble in Δt_i then
        turn into sleeping mode
    end
    else
        if S_i^j then
            broadcast the preamble and data
        end
        else
            waiting for available spectrum
        end
    end
end
else
    turn to sleep mode
end
```

III. PERFORMANCE EVALUATION

In this section, we evaluate the performance of CRB-RPL under different scenarios. We implement CRB-RPL with the topology as shown in Fig. 1. Other simulation parameters are given in TABLE I. We consider a square region of side 1200 meters that is occupied by 16 PU transmitters. The secondary users are assumed to be Poisson distributed in the whole region as shown. We consider a frequency selective Rayleigh fading channel between any two nodes. For performance comparison, we also implement CORPL and RPL in CR environments.

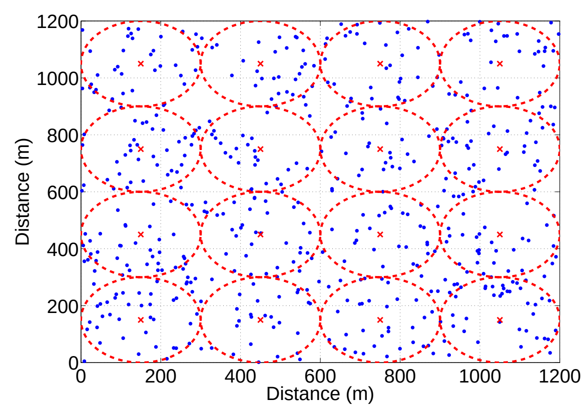

Fig. 1. Simulated network topology. The circles represent the coverage area of PU transmitters.

TABLE I
SIMULATION CONFIGURATION PARAMETERS

Parameter	Value
Path loss model	$128.1 + 37.6\log_{10}(r)$
Carrier frequency	2 GHz
Standard deviation of shadowing	8 dB
Detection probability threshold(P_d)	0.9
Probability of false alarm (P_f)	0.1
Channel bandwidth	200KHz
PU received SNR(γ)	-15dB
Size of DIO message including options	28 bytes
Checking interval (T_{CI})	144 ms
Preamble length (T_{pr})	144 ms
Transmission time of a data packet (T_d)	4 ms
Transmission time of one micro-frame (T_m)	40 μs
Time from sleep mode to active mode (τ)	88.4 μs

First, we evaluate the impact of the link outage probability on the DAG convergence time. As Fig. 2, the DAG convergence time decreases as the link success probability (LSP) increases due to lower link layer retransmissions as shown. Note that the DAG convergence time reduces as the node density increases. This is because a higher density results in faster dissemination of network information owing to more nodes in the coverage range.

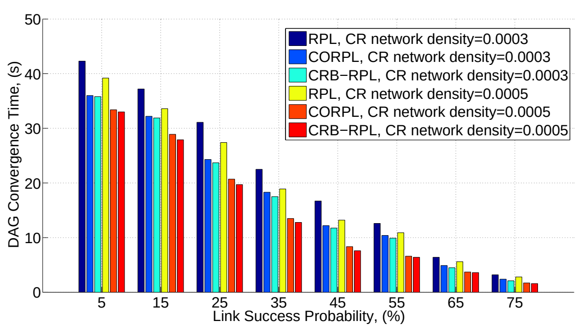

Fig. 2. DAG convergence time against LSP. The DAG convergence time decreases as LSP increases and network density increses

Next, we evaluate the performance in terms of *Packet Delivery Ratio* (PDR) which is defined as the ratio of number of packets received to the total number of packets sent. PDR captures the fraction of packets sent by different nodes that are actually delivered to the gateway. We generate 10,000 packets (packet size = 100 bytes) from different nodes and calculate the average PDR for different scenarios as shown in Fig. 3. It is evident from the results that CRB-RPL outperforms RPL and CORPL. The performance gain is significant under poor channel conditions (low LSP). CRB-RPL exploits the broadcast nature of wireless medium and multiple receivers competition improves the PDR by reducing retransmissions. Hence, the CRB-RPL can get a good performance as well as CORPL $classA$ route and higher than CORPL $classB$ route.

We also evaluate the transmission time performance of CRB-RPL. The results in Fig. 4 evaluate the *Deadline Violation Probability* (DVP) for delay sensitive alarms under different scenarios. The DVP decreases as the LSP increases due to lower link layer retransmissions that decrease the remaining

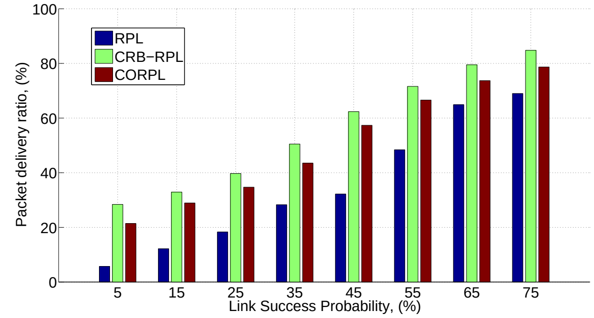

Fig. 3. PDR performance comparison for different protocols. CRB-RPL has the best performance in the comparison.

lifetime of a packet at the intermediate nodes and therefore, the packet is dropped before reaching the gateway. CRB-RPL provides enhanced performance compared to CORPL and RPL as the dynamic sensing time is adopted. Especially, when the LSP is high, the spectrum sensing time can be shortened obviously.

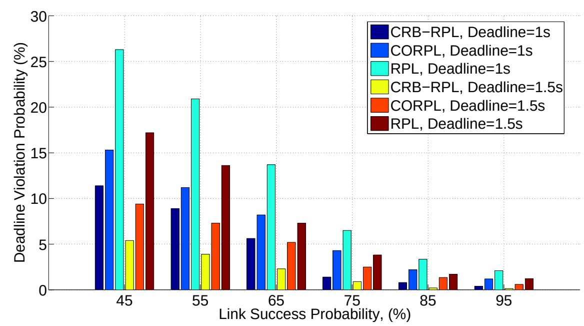

Fig. 4. Deadline Violation Probability for different scenarios. DVP decreases as LSP and deadline increase.

Last, we evaluate the level of protection for PU receivers in terms of *Collision Risk Factor* (CRF), which is defined as the ratio of colliding transmissions to the total number of secondary node transmissions at the PU receivers. Hence CRF depends on PU transmitter activity and coverage overlap between secondary nodes and PU transmitters. As shown in Fig. 5, CRB-RPL reduces the chances of collision to PU receivers compared with CORPL under both low and high PU transmitter activity. Note that the CRF increases with increased PU activity and secondary node transmission range due to higher probability of collision with PU receivers.

IV. CONCLUSIONS

A fundamental challenge in Cognitive Radio based AMI networks is the efficiency and reliability for different application in order to realize the vision of smart grid. Considering the promising future of cognitive smart grid networks, we propose CRB-RPL; which is an enhanced RPL protocol based on receiver-based routing for cognitive radio enabled AMI networks. CRB-RPL utilizes the CRTF for rank compute, which includes consideration of both QoS and protection of PU. Its inherently receiver-based character caters for efficiency

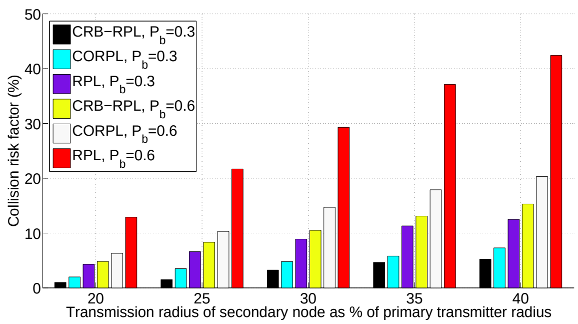

Fig. 5. Collision risk factor against secondary nodes transmission radii. CRF increases as secondary node transmission radius and P_b increase.

and reliability requirements of Cognitive Radio based AMI networks. Simulation results show that CRB-RPL improves the efficiency and reliability of the network while reducing harmful interference to PUs. Hence, CRB-RPL provides a viable solution for practical cognitive AMI networks. The future work will focus on analysis of CRB-RPL under the dynamics of power systems.

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